WL-TR-95-5002

EXPLORATORY LASERS

Kenneth L. Schepler
Electro-Optics Sources Branch
Electro-Optics Technology Division

JANUARY 1995
Final Report for Workunit 20010501
Oct 1980 - Dec 1994

DTIC
S ELECTE D
MAY 1 8 1995
G

Approved for public release; distribution unlimited.

Solid State Electronics Directorate
Wright Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7405

19950517 091

DTIC QUALITY INSPECTED 5

NOTICE

WHEN GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY GOVERNMENT-RELATED PROCUREMENT, THE UNITED STATES GOVERNMENT INCURS NO RESPONSIBILITY OR ANY OBLIGATION WHATSOEVER. THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED OR IN ANYWAY SUPPLIED THE SAID DRAWINGS, SPECIFICATIONS, OR OTHER DATA, IS NOT TO BE REGARDED BY IMPLICATION, OR OTHERWISE IN ANY MANNER CONSTRUED, AS LICENSING THE HOLDER, OR ANY OTHER PERSON OR CORPORATION; OR AS CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

This report is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Kenneth L Schepler

KENNETH L. SCHEPLER, PhD
Research Physicist
Electro-Optics Sources Branch

Donald J Smith

DONALD J. SMITH, Chief
Electro-Optics Sources Branch
Electro-Optics Division

C. Richard Lane

C. RICHARD LANE, Actg Chief
Electro-Optics Division
Solid State Electronics Directorate

If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization, please notify, WL/ELO Building 22B, 2700 D Street, Ste #2, Wright-Patterson AFB OH 45433-7405 to help us maintain a current mailing list.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	94 Jan	Final, Oct 80 - Dec 94

4. TITLE AND SUBTITLE

Exploratory Lasers

5. FUNDING NUMBERS

PR - 2001
TA - 05
WU - 01
PE - 62204F

6. AUTHOR(S)

DR. KENNETH L. SCHEPLER, WL/ELOS, WPAFB OH

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Electro-Optics Sources Branch
Wright Laboratory Air Force Command
Wright-Patterson AFB OH 45433-7405

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Solid State Electronics Directorate
Wright Laboratory
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7405

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

WL-TR-95-5002

11. SUPPLEMENTARY NOTES

Approved for public; distribution is unlimited

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This document is the final report for work unit 20010501. The objective of this work unit was to improve performance of existing lasers and to demonstrate new laser source concepts in line with Air Force mission needs. Technical accomplishments are briefly reviewed with references to more detail in previous publications.

14. SUBJECT TERMS

Lasers, tunable lasers, nonlinear optics, nonlinear frequency conversion

15. NUMBER OF PAGES

16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

TABLE OF CONTENTS

Accesion For

NTIS CRA&I ☒
DTIC TAB ☐
Unannounced ☐
Justification

By
Distribution /

Availability Codes

Dist	Avail and / or Special
A-1	

Capt. Brian Smith

Mr. Don (Sandy) Smith

Mr. Gary Smith

Mr. Bob Wade

Capt. Betsy Ziegler

In addition, the following visiting scientists, collaborators, and students made valuable contributions:

Dr. Norman Barnes	NASA-Langley, collaboration
Mr. Peter Budni	Lockheed-Sanders, collaboration
Dr. Gary Catella	Cleveland Crystals, collaboration
Mr. Evan Chicklis	Lockheed-Sanders, collaboration
Mr. D. G. Cooper	NRL, collaboration
Mr. William Deleranko	Wright State U., masters thesis
Dr. Leon Esterowitz	NRL, collaboration
Ms. Jennifer Foley	High School Apprentice
Mr. Mark Knights	Lockheed-Sanders, collaboration
Dr. Milan Kokta	Union Carbide, collaboration
Dr. Charles Marquardt	NRL, collaboration
Dr. Tom Pollak	Lockheed-Sanders, collaboration
Ms. Alison Potter	High School Apprentice
Dr. Steve Rand	University of Michigan AFOSR-sponsored collaboration
Mr. Todd Stockert	High School Apprentice

Dr. Mark Storm	NRL (now NASA), collaboration
Capt. Monte Turner	AFIT masters thesis student
Dr. Silvester Wong	DREV, Quebec, Canada TTCP JTP-10 personnel exchange
Dr. Henry Zenzie	Lockheed-Sanders (now SEO) collaboration

The start of this workunit marked the transition from research on gas and chemical laser to research on solid-state lasers at this laboratory. The problems with size, reliability, and safety in gas and chemical lasers had become evident from previous research efforts. Solid-state lasers offered the potential of smaller size, less complexity, higher reliability, and fewer safety issues. In addition, the potential of developing tunable solid-state lasers offered important advantages in many new applications, both military and commercial.

2. TECHNICAL ACCOMPLISHMENTS

This final report is a brief overview of the research done under workunit 20010501. For detail on a particular area, the papers referenced in the text below and listed in the Appendix may be consulted.

Efforts throughout this program concentrated on the investigation of solid-state lasers with wavelength tunability or wavelength conversion. In-house measurements ranged from basic spectroscopy to performance assessment of commercial laser devices. Emphasis was placed on measurement and evaluation of those properties which could be used to assess the potential of a particular laser medium, nonlinear material, or innovative concept. Air Force requirements in the areas of operating wavelength, efficiency, output power/energy, reliability, maintainability, and safety were the motivating criteria.

Early work concentrated on the investigation of laser crystals doped with transition metal ions. Transition metal ions were found to have broad, continuously tunable output due to the coupling of their electronic energy levels to crystal vibrational levels. Alexandrite was an early success with useful tunability in the 730-780 nm range.[1] Other chromium-doped crystals were investigated but most of them were found to have severe problems with solarization under flashlamp pumping. This resulted in poor

laser performance.[2,3] Investigations of other ions such as Sm^{2+} [4] with the potential for lasing at several lines were also pursued.

Titanium-doped host materials were shown to have great promise as tunable visible lasers.[5] Indeed, titanium sapphire has become a great success with tunability throughout the 700-1000 nm range and with numerous commercial devices now available. However, temperature dependent spectroscopic investigations of titanium doped into other crystal hosts [6-10] showed that sapphire had an optimum crystal field strength. In hosts with weaker crystal fields, the nonradiative losses became severe at room temperature. In hosts with stronger crystal fields, such as $YAlO_3$, gain was not observed possibly due to excited state absorption into the conduction band of the host lattice.

Co-doping of chromium and neodymium in garnet hosts was investigated.[8,11] Cr^{3+} ions were found to be more efficient absorbers of flashlamp radiation than rare earth ions such as Nd^{3+}. In certain garnet crystals co-doped with Cr^{3+} and Nd^{3+} ions, chromium ions efficiently transferred their excitation to neodymium ions resulting in flashlamp pumped laser efficiencies approaching 10%, twice that of Nd:YAG. However, garnet crystals with efficient energy transfer were also found to have thermal lensing at least twice as strong as YAG.

In the late 1980's emphasis was placed on development of a

tunable, mid-IR laser useful for infrared countermeasures. Because they operated only at discrete wavelengths, rare earth lasers alone did not meet the tunability criterion. However, nonlinear frequency conversion appeared to be a viable solution.[12,13] For that reason considerable effort was devoted to the characterization and development of optical parametric oscillators (OPO's) and difference frequency mixers capable of generating 2-5 μm tunable output. $AgGaSe_2$ was shown to work well as a mid-IR OPO pumped at 2 μm with conversion efficiencies near 30% at kilohertz repetition rates and output powers approaching 1 W.[14-18] However, at pump powers above 4 W, $AgGaSe_2$ was found to have severe thermal lensing problems which prevented scaling to output powers greater than 1 W.[19,20] In addition, surface damage limited energy densities that could be safely applied to an OPO crystal surface.[21]

Modeling of nonlinear interactions was done to better understand and improve upon the limitations of current frequency conversion techniques.[22] Although the basic theory is known, the details of threshold and conversion efficiency are still poorly understood.

Nonlinear interactions using 1-μm laser pumping, both difference frequency generation and OPO's, were investigated as an alternative to 2-μm pumped frequency conversion.[23-25] Use of a 1-μm Nd:YAG pump laser has the advantage of using well-

developed pump laser technology. Also, the KTP-type nonlinear crystals have been shown to be more damage resistant than chalcopyrites like $AgGaSe_2$. Efficient conversion has been demonstrated but generation of emission beyond 4 μm with available nonlinear crystals has not been possible due to absorption features at long wavelengths.

3. CONCLUSIONS

The technical accomplishments of this effort have had a major role in developing solid-state lasers to meet Air Force needs. Solid-state tunable visible lasers are now commercial devices. And breadboard lasers capable of efficient generation of mid-IR output have been demonstrated.

However, the battle is clearly not over with victory declared on all fronts. A number of important issues remain to be addressed, particularly the need for a high average power, high repetition rate, tunable mid-IR laser for a number of Air Force applications. Efforts to advance this technology will be continued under the auspices of an AFOSR-funded Infrared Countermeasures Initiative. Results will be documented under workunit 2301EL01.

4. REFERENCES

1. K. L. Schepler, "Fluorescence of Inversion Site Cr^{3+} Ions in Alexandrite," *J Appl Phys*, **56** (1984), 1314-1318.

2. R. C. Simpson and K. L. Schepler, "Flashlamp Pumped Lasing of Cr^{3+}:GsScGa-Garnet," Conference on Lasers and Electro-Optics, Baltimore, MD, May 1985.

3. K. L. Schepler, "Performance Limitations of Vibronic Lasers," *Laser Research and Development in the Northeast*, Editors: Trainer and Chicklis, Proc. SPIE **709** (1987), 103-108.

4. H. H. Zenzie, T. M. Pollak, E. P. Chicklis, and K. L. Schepler, "Laser Emission at 679.8 nm in $Sm^{2+}:BaMgF_4$," *Topical Meeting on Tunable Solid State Lasers Technical Digest Series*, **Vol 20**, (1987) 150-153.

5. K. L. Schepler, "Laser Performance and Temperature Dependent Spectroscopy of Titanium Doped Crystals," *Tunable Solid-State Lasers II*, **Vol 52**, Editors: Budgor, Esterowitz, and DeShazer (1986), 235-239.

6. K. L. Schepler and M. Kokta, "Spectroscopic Properties of GdScAl Garnet Doped with Ti^{3+}," *J Appl Phys*, **63** (1988), 960-962.

7. K. L. Schepler, "Crystal Field Effects on the Spectroscopy of Ti^{3+} Ions," Topical Meeting on Laser Materials and Laser Spectroscopy (Guide), Shanghai, China, (1988), 64.

8. K. L. Schepler, "Spectroscopy and Laser Performance of Ti^{3+} Doped and Cr^{3+},Nd^{3+} Co-doped Crystals," AFWAL-TR-88-1125, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, 1988.

9. A. L. Potter and K. L. Schepler, "Optical Spectroscopy of Ti^{3+} Doped $YAlO_3$," WRDC-TR-89-5052, Wright Research and Development Center, Wright-Patterson Air Force Base, Ohio, 1989.

10. R. Oliver, R. Wade, and K. Schepler, "Crystal Field Effects on Ti^{3+} Viability as a Laser Material," *OSA Proceedings on Advanced Solid-State Lasers*, Hans P. Jenssen and George Dube, eds. (Optical Society of America, Washington, DC 1991), **Vol. 6**, 115-120.

11. W. H. Deleranko and K. L. Schepler, "Energy Transfer Kinetics in Nd^{3+},Cr^{3+}:GSGG," *Topical Meeting on Tunable Solid State Lasers Technical Digest Series*, **Vol 20**, (1987) 147-149.

12. K. L. Schepler and N. P. Barnes, "Nonlinear Optical Processes for the Mid-IR Region," *Laser Applications in Meterology and Earth and Atmospheric Remote Sensing*, M. Sokoloski, editor, Proc. SPIE **1062**, (1989) 92-97.

13. N. P. Barnes and K. L. Schepler, "Solid State Lasers for the Mid-IR Region," *Laser Applications in Meterology and Earth and Atmospheric Remote Sensing*, M. Sokoloski, editor, Proc. SPIE **1062**, (1989) 2-8.

14. K. L. Schepler, M. E. Storm, C. L. Marquardt, and L. Esterowitz, "Optical Parametric Oscillation in Commercially Produced $AgGaSe_2$," *Topical Meeting on Tunable Solid State Lasers Technical Digest Series*, **Vol 20** (1987), 233-236.

15. K. L. Schepler, M. D. Turner, and P. A. Budni, "High Average Power Nonlinear Frequency Conversion in $AgGaSe_2$," *OSA Proceedings on Advanced Solid State Lasers*, George Dube, Lloyd Chase, eds. (Optical Society of America, Washington, DC 1991), **Vol. 10**, 325-328.

16. K. L. Schepler and P. A. Budni, "High Power $AgGaSe_2$ Optical Parametric Oscillator," Conference on Lasers and Electro-Optics, May 1991, Paper CFM3.

17. P. A. Budni, M. G. Knights, E. P. Chicklis, K. L. Schepler, "High Repetition Rate $AgGaSe_2$ Optical Parametric Oscillator," 1992 OSA Annual Meeting, Sept. 1992, Paper TuWW4.

18. P. A. Budni, M. G. Knights, E. P. Chicklis, and K. L. Schepler, "Kilohertz $AgGaSe_2$ Optical Parametric Oscillator Pumped at 2 µm," *Opt Lett* **18,** (1993) 1068-1070.

19. C. L. Marquardt, P. A. Budni, M. G. Knights, K. L. Schepler, R. DeDomenico, and G. C. Catella, "Thermal Lensing and Power Scaling of a $AgGaSe_2$ OPO," 1992 OSA Annual Meeting, Sept. 1992, Paper TuWW5.

20. C. L. Marquardt, D. G. Cooper, P. A. Budni, M. G. Knights, K. L. Schepler, R. DeDomenico, and G. C. Catella, "Thermal Lensing in Silver Gallium Selenide Parametric Oscillator Crystals," *Applied Optics* **33**, (1994) 3192-3197.

21. B. C. Ziegler and K. L. Schepler, "Transmission and Damage Threshold Measurements in $AgGaSe_2$ at 2.1 μm," *Applied Optics* **30**, (1991) 5077-5080.

22. S. K. Wong and K. L. Schepler, "Non Steady-State Optical Parametric Oscillator Model," 1993 OSA Annual Meeting, Oct. 1993, Paper MO1.

23. D. L. Fenimore and K. L. Schepler, "Three-Wave Nonlinear Interactions in $KTiOPO_4$ (KTP) and KTP Isomorphs," WL-TR-93-5029, Wright Laboratory, Wright-Patterson Air Force Base, Ohio, 1993.

24. S. K. Wong, R. Oliver, and K. L. Schepler, "Difference Frequency Generation of 4-micron Radiation from Nd:YAG Lasers," 1993 OSA Annual Meeting, Oct. 1993, Paper TuD2.

25. S. K. Wong, R. Oliver, K. L. Schepler, and D. L. Fenimore, "Difference Frequency Generation of 4-μm Radiation from Nd:YAG Lasers," *Opt Lett* **19**, (1994) 1433-1435.